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At the 27th annual International Symposium on Compound Semiconductors in Monterey, CA, USA many advanced technologies were covered, including such innovative topics as nano-column-supported gallium nitride, solar-blind aluminium gallium nitride Metal-Semiconductor-Metal photodetectors, and the latest developments in III-V MOSFETs.

Nano-column GaN, III-V MOSFETs and more...

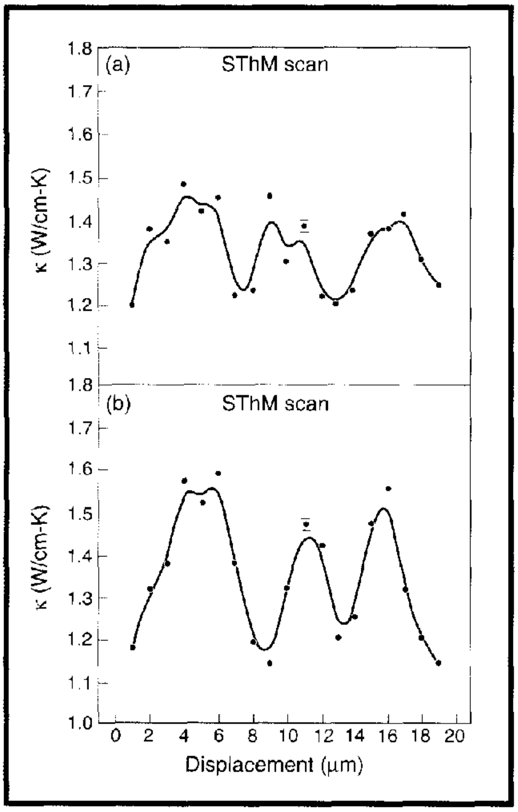

Figure 1: Thermal conductivity (solid squares) of two HVPE-grown n-GaN samples, measured by scanning thermal microscope. Representative error bars are shown. The solid lines are guides to the eye.

The GaAs HBT revolution was started as long as 10 years ago by TRW opening an MBE production line for space applications of MMICs. Now, "TRW and its licensee, RF Micro Devices, have over 20% of the world's power amplifier market", according to TRW's Dwight Streit

Last October's ISCS was notable for the apparence of the great increase in epitaxial production capacity (both MBE and MOCVD). Most companies now have epitaxy production capabilities, with MOCVD gaining the larger share of production volume for both optoelectronic and, more recently, electronic devices.

But the gallium arsenide HBT revolution was started as long as 10 years ago by TRW opening an MBE production line for space applications of MMICs. This early commitment placed TRW well ahead in the growing cell-phone market, where the benefits of HBT characteristics (low 1/f noise, high early voltage, excellent power-added efficiency and highly linear output properties) made GaAs devices the popular choice for the latest phones. Indeed, in the opening invited plenary talk on the "Evolution of Gallium Arsenide HBTs in Cellular and Fibreoptic Applications" Dwight Streit of TRW's Space and Electronics Group stated that TRW and its licensee, RF Micro Devices, have over 20% of the world's power amplifier market. TRW has also developed a high-frequency (up to 50 GHz) high-beta HBT process with a current gain of 600 and current densities of 40 kA/cm^2.

Though originally developed for space applications, the success of GaAs HBTs (including revolutionary changes in the ease of cell-phone operation) has provided a large growth market and changed the perception of this technology, with them now finding many uses in fibre-optic digital circuits operating at frequencies of 10 Gbps and above. However, TRW and RFMD may find more competition in these markets as the large increases in the installed MOCVD capacity for the production of similar HBTs comes on-stream. TRW now has a production capability for indium phosphide HBTs, which are finding application in the higher-frequency ranges including 40 Gbps fibre systems.

In the second invited plenary talk Jim Palmour from Cree Inc presented the latest perspective on "Silicon Carbide and Gallium Nitride Devices on Semi-Insulating Substrates". Because of their wide bandgap and high breakdown voltages, their devices offer a wide range of high-frequency and high-power functions, with GaN the preferred material system for device operating frequencies above 8 GHz.

In the high-power-density applications typical for these devices, SiC MESFETs operate at 50-60V drain biases and GaN HEMTs in the 30-40V range, generating very high thermal power densities (in the range of Watts per mm^2). Long a proponent of SiC, Cree believes that this material - with thermal a conductivity as high as 4.9 W/cmK - is the ideal substrate for both material systems, allowing a 30 W device to be only a quarter the size of a 30 W silicon device. However, most of the heat generated passes through to the package, requiring new package designs to provide the complete heat removal solution. Unfortunately, the relatively high cost of carbide substrates is still restricting the wider application of these devices.

The latest achievements for SiC include an MIM capacitor that withstands 200 V and the highest power reported to date from a single device of 120 W at 3.1 GHz from a 48 mm FET operating under pulsed conditions. Using GaN active layers, Cree also presented their first AlGaN/GaN HEMT-based MMIC with a record peak power output level of more than 20 W at 9 GHz and an associated gain of 14.1 dB (reported in Issue 5, p21).

Materials advances

(i) Higher thermal conductivity for GaN

The importance of device thermal conductivity was noted earlier, so the thermal conductivity of Group III nitrides could be an important factor for device design. Very little has been reported on this topic and the accepted values for GaN thermal conductivity are in the range 1.2-1.4 W/cmK. In the latest work reported by Fred Pollak *et al* from the Brooklyn College of CUNY in cooperation with Bo Monemar *et al* from Linkoping University, a scanning thermal microscope has been used to examine the thermal conductivity of GaN grown on sapphire substrates. This thermal microscope has a platinum-rhodium tip which is positioned like an atomic force probe near the material surface, providing non-destructive thermal sensing with very high spatial resolution (2-3 µm). Typical thermal scans from two HVPE samples are shown in Figure 1.

This new tool has been used to probe GaN layers, both HVPE and MOCVD grown (20-25 and 2.5 µm thick, respectively) and has demonstrated a correlation between the thermal conductivity and material dislocations and grain boundaries. Any defects in a crystal lattice lower its

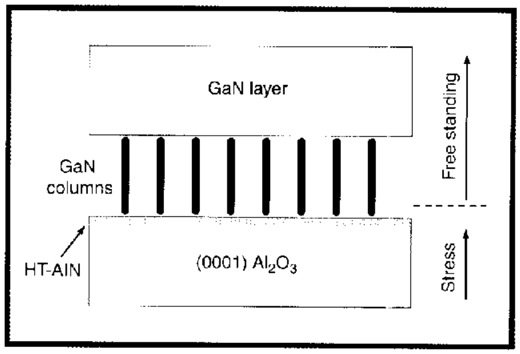

Figure 2. Diagram of the nano-column structure.

conductivity, thus higher conductivity is found in the lower-defect-level regions. When investigating lateral epitaxially overgrown GaN, the highest value yet reported for GaN conductivity, kappa (κ), of 2.1 W/cmK was measured over the low-defect regions, while the higher-defect-level window regions remained at $\kappa = 1.2$. As defect levels are reduced in GaN substrates, even higher values for GaN conductivity κ should be achievable and could exceed that of many metals, allowing even better heat dissipation properties than are available today.

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As may be anticipated, preliminary conductivities determined for bulk aluminium nitride were higher than for gallium nitride. These results are quite significant, because the higher the thermal conductivity that can be demonstrated for gallium nitride the less the need will be for high conductivity substrates for gallium nitride power electronics. Work is in progress to determine the thermal conductivity for aluminium gallium nitride.

(ii) Nano-column-supported GaN

Extending the ways to produce free-standing GaN is an on-going quest and Kazuhide Kusakabe from Sophia University, Japan described a new approach to the growth of quasi-free-standing GaN on sapphire. In this process a self-organized nano-column structure of epitaxial GaN with column diameters of about 100 nm is produced as a footing or buffer layer (see Figure 2). This represents a density of about 1×10^{10} per cm^2 and provides an air-bridge-type structure on which to grow relaxed (strain-free) layers of GaN (Figure 3).

"A self-organised nano-column structure of epitaxial GaN...provides an air-bridge-type structure on which to grow relaxed (strain-free) layers of GaN"

Sapphire substrates for the GaN nano-column growth process receive a thermal clean (30 min at 900°C) followed by the deposition of a high-temperature 12 nm aluminium nitride "nucleation layer" to form a "coalescence zone" grown by RF-plasma assisted MBE (RF-MBE) at a rate of 2.3 µm/hr. The deposition of the silicon-doped

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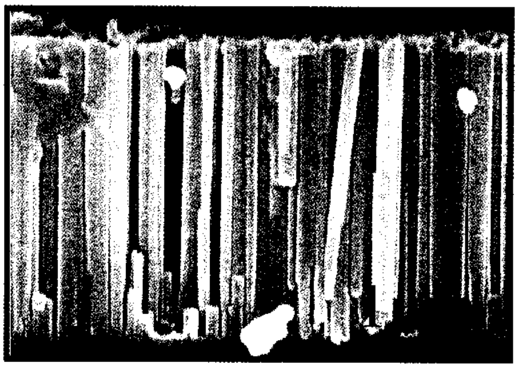

Figure 3. Micrograph of the nano-columns.

GaN followed at a rate of 7.2 μm/hr to form the coalesced quasi-free-standing layers of GaN 2.9 μm thick.

The crystal *c*-axis dimension of 5.185Å is often used as an indication of strain-free GaN, which can be obtained by growing MOVPE or HVPE layers of GaN of thicknesses 100 μm or greater. However, after only 2 μm of growth the *c*-axis dimension of the nano-column-supported layer was the strain-free gallium nitride value of 5.185Å. The strain-free layers can be easily stripped from the supporting columns.

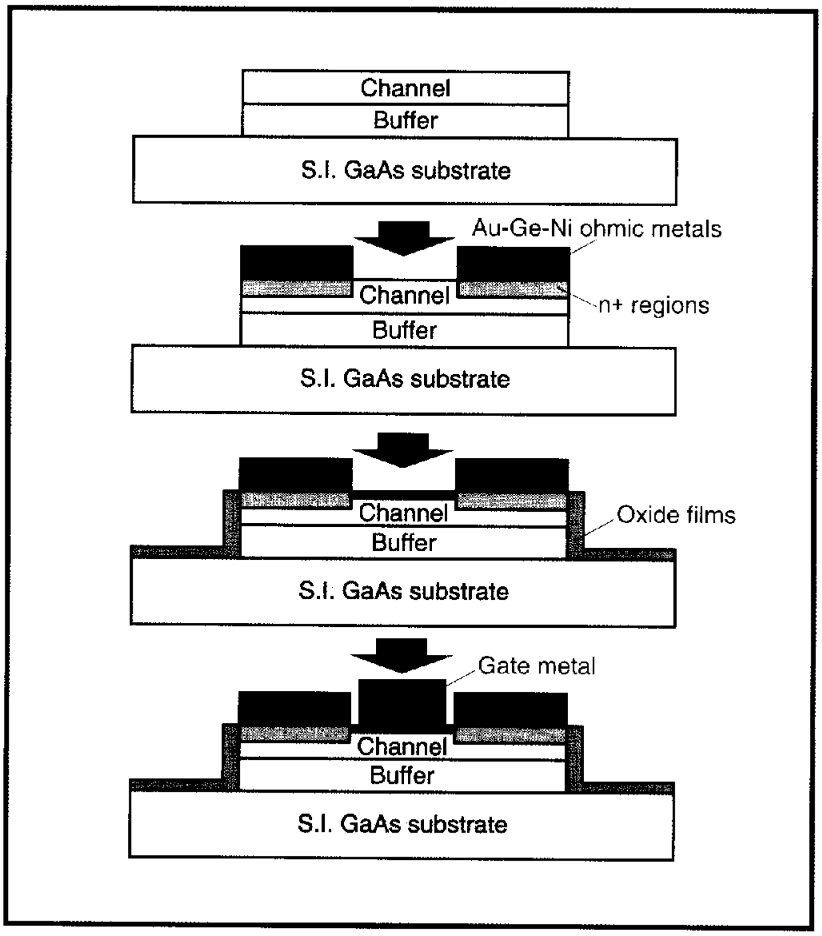

Figure 4. Process flow diagram of a GaAs MOSFET with selective oxidation technology by using metal as the mask.

(iii) Laser lift-off for GaN devices

High-power uses of GaN devices on sapphire substrates (lasers in particular) can create either reduced performance or potential heat dissipation and device lifetime problems. Therefore, the ability to transfer active devices to other substrates offers potential advantages for commercial equipment such as laser printers.

In his paper "The Integration of InGaN-based Optoelectronics with Dissimilar Substrates by Wafer Bonding and Laser Lift-off", William Wong from Xerox Palo Alto Research Center described the successful transfer of AlGaN devices to other materials. In this xenon chloride eximer laser process (originally described by T Sands from University of California, Berkeley), only the interfacial GaN layer reaches a temperature high enough to separate the pre-fabricated, fully functional device, thus protecting the functional device layers.

Various transfers of 3 μm GaN membranes were described, such as the transfer of LEDs to quartz without changing their current-voltage characteristics; the transfer of multi-quantum well (MQW) InGaN laser diodes to copper substrates (where the copper can be used as a back contact and to enhance the diode performance) and the transfer of similar devices to silicon substrates. A palladium-indium mixture (1:3) can be used to fill any voids at 156°C. Wong noted that the successful transfers "from sapphire to copper demonstrated the efficacy of this process to integrate these lasers onto virtually any substrate material" and open up a wide range of new applications.

Solar-blind detectors

B Yang *et al* from the University of Texas at Austin reported the development of the first back-illuminated solar-blind metal-semiconductor-metal (MSM) detectors.

The device structure was made from AlGaN epitaxial layers grown by low-pressure MOCVD on a sapphire substrate. The active structure was formed by growing an 0.8 μm window layer (60% Al) over an AlN buffer layer, followed by a 10 nm transition layer (Al graded from 60 to 40%) and then the 0.2 μm active AlGaN layer (Al 45%). After defining mesas by reactive ion etching, metal contacts were formed by the evaporation of titanium (50Å) and platinum (800Å). Passivation was provided by PECVD silicon dioxide (1000Å).

The 40x40 μm MSM photodetectors produced by this AlGaN process had dark currents lower than the detection limit of the equipment (20 fA) at up to 100 V bias voltages. External quantum efficiencies were as high as 48% and cut-off sensitivities at about 280 nm wavelengths, providing the first high-performance, back-illuminated, solar-blind AlGaN MSM photodetectors.

III-V MOSFETs

(i) Low-temperature wet chemical process

As more results are reported, GaAs MOSFETs move closer to commercial reality. Jau-Yi Wu from Taiwan's National Cheng-Kung University reported on low-temperature selective chemical oxidation for growth of gate oxides on GaAs.

In this novel wet chemical process (see Figure 4) gold-germanium-nickel contact metals are deposited, delineated, annealed and then used as a mask for the oxidation process. Wu reported that by using this new selective liquid-phase oxidation process, a composite gate dielectric is formed on the GaAs (a mixture of gallium oxide, arsenic and arsenic sesquioxide), which exhibits better stability, lower leakage currents and better *I-V* characteristics than conventionally deposited oxides. With a 350Å-thick gate oxide, the GaAs MOSFET - an n-channel depletion mode device - had a reverse leakage current of 1.5×10^{-4} A/cm^2 at a bias of -5 V. The forward leakage current was in the same range at +5 V. Transconductance values of 80 mS/mm were reported at operating frequencies of 3.6 GHz for 2 µm gate length devices.

(ii) Single-crystal rare-earth oxides on GaN

In an extension of their development of MOS devices in III-Vs, Minghwei Hong *et al* from Bell Labs (Lucent Technologies, Murray Hill, NJ, USA) reported the first epitaxial single-crystal growth of both gadolinium and yttrium oxides on GaN.

Initially, these epitaxial rare-earth films were grown on silicon and had cubic structure, exhibiting low leakage currents, low interfacial densities of states and high dielectric constants - all useful properties for replacing silicon dioxide in silicon devices. However, when the epitaxial films were grown on MOCVD-produced, sapphire-based GaN, the gadolinium and yttrium oxides were in the hexagonal phase. In spite of large lattice mismatches with the GaN sub-layer, the epitaxial oxide films were fully relaxed and of excellent crystal quality, so it is presumed that the misfit dislocations are being trapped near to the nitride/oxide interface.

These high-quality rare-earth oxide films have potential uses in nitride electronics, with the first GaN MOSFET based on them also reported.

(iii) First GaAs Complementary MOS

In another rare-earth gate-oxide development at Bell Labs, Minghwei Hong reported the first GaAs complementary MOS devices.

A complementary MOSFET inverter was made using mixed gallium/gadolinium oxide as the gate dielectric, deposited by oxygen-free electron-beam evaporationt. With gadolinium content of >40%, there is a good semiconductor-to-oxide interface and low leakage currents. There is no direct current pass on this device since either the p- or the n-transistor is in the off state. The n-MOSFET shows relatively high leakage currents and low mobility in this III-V CMOS device, but these characteristics were believed to be a consequence of the non-self-aligned gate design that was used.

Such MOSFETs, together with nano-column GaN and solar-blind detectors, show how compounds continue to create many new market opportunities.

"Bell Labs also reported the first gallium arsenide complementary CMOS device... made using the mixed gallium/gadolinium oxide as the gate dielectric"